

Climate and land use change impacts on plant distributions in Germany

Sven Pompe^{1,*}, Jan Hanspach¹, Franz Badeck², Stefan Klotz¹, Wilfried Thuiller³ and Ingolf Kühn¹

¹Department of Community Ecology, UFZ, Helmholtz Centre for Environmental Research-UFZ, Theodor-Lieser-Strasse 4, 06120 Halle, Germany

²Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany

³Laboratoire d'Ecologie Alpine, UMR CNRS 5553, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France

*Author for correspondence (sven.pompe@ufz.de).

We present niche-based modelling to project the distribution of 845 European plant species for Germany using three different models and three scenarios of climate and land use changes up to 2080. Projected changes suggested large effects over the coming decades, with consequences for the German flora. Even under a moderate scenario (approx. +2.2°C), 15–19% (across models) of the species we studied could be lost locally—averaged from 2995 grid cells in Germany. Models projected strong spatially varying impacts on the species composition. In particular, the eastern and southwestern parts of Germany were affected by species loss. Scenarios were characterized by an increased number of species occupying small ranges, as evidenced by changes in range-size rarity scores. It is anticipated that species with small ranges will be especially vulnerable to future climate change and other ecological stresses.

Keywords: climate change; predictive modelling; plant ranges; Germany

1. INTRODUCTION

Species ranges are not static. Recent climate warming has resulted in species' ranges shifting polewards or to higher altitudes and is recognized as a major threat to biodiversity (Parmesan 2006). On grid-based macro-scales, studies have shown that climate change may lead to dramatic range reductions (Thuiller *et al.* 2005). However, the magnitude and spatial pattern of potential range changes, as well as effects on local plant biodiversity, still need to be studied in detail. A key issue in conservation ecology is the understanding of how future climate and land use changes affect the species distributions at the national level. Therefore, the modelling task involves testing predictive techniques and understanding possible impacts of climate change on regional to local scales. However, at increasingly smaller scales, parameters like soil factors or land use become

Electronic supplementary material is available at <http://dx.doi.org/10.1098/rsbl.2008.0231> or via <http://journals.royalsociety.org>.

One contribution of 12 to a Special Feature on 'Global change and biodiversity: future challenges'.

increasingly important (Pearson & Dawson 2003). Including such predictors has been shown to improve the accuracy of species' distribution models (Jetz *et al.* 2007; Luoto *et al.* 2007).

Here, we use three representative models to characterize species' requirements concerning climate, soil and land use (see Pearson *et al.* 2004). Our modelling framework integrates effects of future climate and land use changes and forecasts expected changes in the occurrence of plant species for Germany. We compare spatial patterns of changes in species' ranges to examine potential consequences for local species richness (SR), which include species currently distributed in Germany as well as those that are currently absent, but may find suitable climatic conditions in the future.

2. MATERIAL AND METHODS

(a) Species and environmental data

We used binary plant distribution data from the Atlas Florae Europaeae (AFE, Jalas & Suominen 1972–2004). We selected 845 species (only species present in more than 50 grid cells) in AFE, of which 550 are currently recorded in Germany. The remaining 295 have not been observed in Germany according to the national floristic database FLORKART (www.floraweb.de). Niche-based models were characterized in ecological space by climatic, soil and land use parameters at the European level. The spatial extent of our data covered 2141 grid cells from the AFE grid (50×50 km² resolution), excluding most eastern European countries (figure S1 in the electronic supplementary material). We calculated percentages of soil characteristics (figure S2 in the electronic supplementary material) for both the AFE grid and the 6'×10' resolution (European Soil Database 2004). Climatic data were computed as monthly averages for 1961–1990 (reference period) and 2051–2080 (future scenarios) at a 10'×10' resolution (Mitchell *et al.* 2004). Scenarios for climate and land use were based on three alternative storylines (Spangenberg 2007) of the ALARM project (Settele *et al.* 2005), namely moderate Sustainable Europe Development Goal (SEDG, climate derived from IPCC SRES scenario B1), intermediate Business As Might Be Usual (BAMBU, A2) and severe GRowth Applied Strategy (GRAS, A1FI). The corresponding average increases in annual mean temperature between reference and scenario periods were 2.2, 2.9 and 3.8°C for SEDG, BAMBU and GRAS, respectively. We calculated 38 bioclimatic variables for both the reference period and the future (table S1 in the electronic supplementary material). We included four land use classes at the 10'×10' grid resolution from PELCOM for the baseline in 2000 and land use in 2080: forest; grassland; cropland; and urban landscape (Mucher *et al.* 2000; Rounsevell *et al.* 2006). We used a spatial join in ArcGIS v. 9.1 software to link grid cells in Germany with the data from 10'×10' layers. Finally, we applied a principal component analysis on the bioclimatic variables and a correspondence analysis (CA) on the soil data to avoid multi-collinearity. Six principal components (explained variance: 93%) and six CA axes (explained variance: 56%) were subsequently used as model predictors.

(b) Model calibration and projection

Data were randomly divided into a calibration (70%) and an evaluation (30%) dataset on the European scale. We used generalized linear models (GLMs), generalized additive models (GAMs) and random forests (RFs) in the R-based BIOMOD package (Thuiller 2003). All models generally had substantial agreement when trained on the calibration dataset and evaluated on the remaining data. Kappa coefficients were 0.62±0.13 (mean±s.d.) for GLMs, 0.64±0.12 for GAMs and 0.68±0.11 for RFs, averaged over all species. We calculated the contribution of predictors to the total variance of the regression model by hierarchical partitioning (Mac Nally 1996). On average, climate explained most of the variance (59±12%), followed by soil (25±10%) and land use (16±7%, figure S2 in the electronic supplementary material). The calibrated models were used to project species distributions for the recent past (1961–1990) and the future (2051–2080) at a finer resolution for Germany. Probability surfaces were transformed into presence/absence maps using thresholds maximizing Cohen's Kappa statistic. Combining bioclimatic, soil and land use variables improved model performance compared with a pure bioclimatic model (figure S3 in the electronic supplementary material). To evaluate species' range changes, we summed the number of grid cells potentially lost and gained by

Table 1. Estimated mean $\pm$ s.d. of species loss, gain and turnover rates in 2051–2080 relative to 1961–1990 for different scenarios and models in Germany under universal dispersal.

model/ scenario	loss per grid cell (%)			gain per grid cell (%)			turnover per grid cell (%)		
	SEDG	BAMBU	GRAS	SEDG	BAMBU	GRAS	SEDG	BAMBU	GRAS
GLM	15 $\pm$ 5	20 $\pm$ 6	35 $\pm$ 10	14 $\pm$ 6	17 $\pm$ 7	21 $\pm$ 8	25 $\pm$ 5	32 $\pm$ 6	46 $\pm$ 9
GAM	15 $\pm$ 7	19 $\pm$ 7	34 $\pm$ 12	15 $\pm$ 7	17 $\pm$ 8	21 $\pm$ 9	26 $\pm$ 6	31 $\pm$ 6	32 $\pm$ 6
RF	19 $\pm$ 9	23 $\pm$ 11	39 $\pm$ 18	25 $\pm$ 11	30 $\pm$ 12	36 $\pm$ 13	35 $\pm$ 9	40 $\pm$ 10	54 $\pm$ 15
average	16 $\pm$ 8	21 $\pm$ 8	36 $\pm$ 14	18 $\pm$ 10	21 $\pm$ 11	26 $\pm$ 12	28 $\pm$ 8	34 $\pm$ 9	49 $\pm$ 12

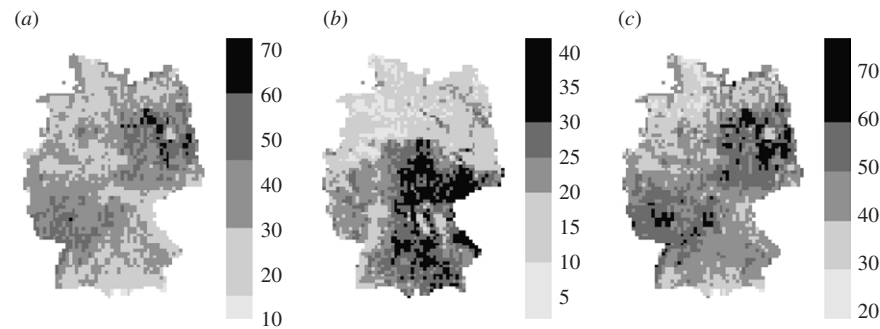


Figure 1. Percentages of species (a) loss, (b) gain and (c) turnover from GLM ($6' \times 10'$) for the GRAS scenario for Germany. Modelled estimates of loss, gain, turnover across models (GLM, GAM and RF) showed high agreement (table S2 in the electronic supplementary material).

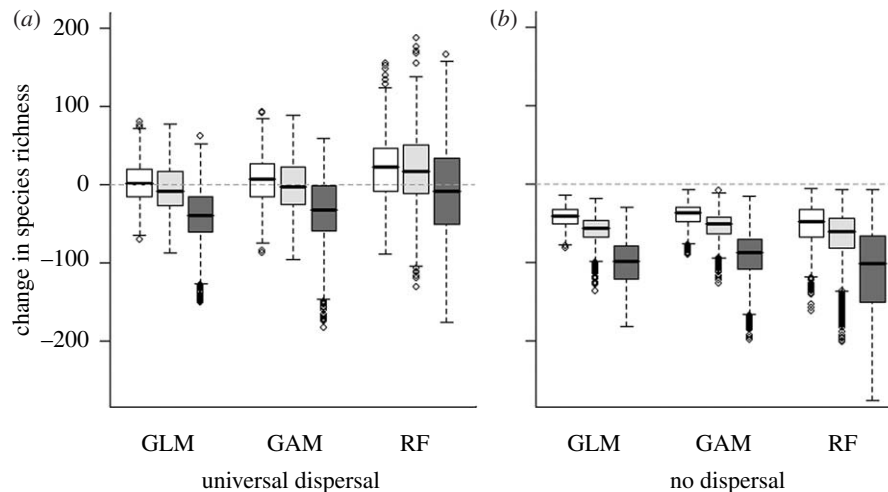


Figure 2. Estimated change in SR (a) using no limitation in species dispersal and (b) with limitation in dispersal computed as difference between modelled future and current SR per grid cell ($n=2995$ grid cells, 845 species). White boxes, SEDG; light grey boxes, BAMBU; dark grey boxes, GRAS.

each species for the different models and scenarios at a $6' \times 10'$ resolution grid. We computed changes in SR estimates for each grid cell between current and future projections applying two dispersal scenarios: full dispersal and no dispersal. Further, we computed losses (L), gains (G) and turnover ($T=100(L+G)/(SR+G)$) per grid cell. As a measure of change in range size, we calculated the differences of inverse range sizes for each grid cell (i.e. range-size rarity). Hence, we calculated the sum of the inverse of the number of grid cells occupied by each of the 845 species for the present and the future (Kier & Barthlott 2001). Rarity scores were divided by the modelled species numbers per grid cell. A low score indicates a grid cell containing species that are present in many other cells, while a high score indicates a cell containing species being present only in a few cells.

3. RESULTS

We found changes in species range sizes parallel to the severity of the scenarios. Approximately 20% of the

species currently present in Germany lost more than 75% of their current range under GRAS, 11% under BAMBU and 7% under SEDG averaged across models.

However, projected range changes showed variations across models. For GRAS, 0% (RF), 4% (GAM) and 5% (GLM) of the currently observed species were projected absent by 2080. The number of currently absent species shifting their ranges to Germany also differed between methods. While RF projected that all 295 species would find suitable conditions in Germany, GLM and GAM were selective and projected roughly half of the species to occur in Germany (42–53%, respectively, across scenarios). Results of local species loss and gain for the 2995 grid cells in Germany coincide with the

severity of the scenarios (table 1). The rate of loss per degree of temperature change increased from SEDG to BAMBU to GRAS, while the rate of gains slowed down, indicating nonlinear responses in species numbers (figure S4 in the electronic supplementary material). The spatial distribution of change generally showed considerable variation. In particular, the southwestern and eastern parts of Germany were affected by high rates of turnover and loss (figure 1). The spatial pattern of gain was substantially different. Mainly, the central and southern parts of Germany were affected by species gains. Projected SR in the full migration case varied substantially across scenarios (figure 2). Under BAMBU (exception RF) and GRAS, SR estimates significantly decreased while under SEDG, median SR significantly increased in all models. Under the assumption of no dispersal, SR decreased significantly in all models ($p < 0.05$, paired Wilcoxon signed-rank test). In addition, range restrictedness increased. When comparing current and future range-size rarity indices, we found a significant increase within all models and across scenarios ($p < 0.05$, paired Wilcoxon signed-rank test; figure S5 in the electronic supplementary material).

4. DISCUSSION

Our study is currently the first comprehensive estimation of how the ranges of plant species at the resolution of a national floral atlas in Central Europe could change under climate and land use changes. These projected changes suggest that the German flora will be impacted negatively, even under the moderate climate/land use change assumptions. Species currently not recorded in Germany will cause severe changes in the species pools. New species move in as climate warming increases. Potential gains from non-European species were not included. We show that eastern and southwestern Germany will be greatly affected, which previously has not been recognized (Thuiller *et al.* 2005). From this study, it appears that certain regions in Germany are characterized by higher range-size rarity under climate change. Given the fact that ranges will be smaller in the future, the species in these regions may be less able to respond to additional stresses, e.g. habitat fragmentation. However, our approach ignores the differentiated dispersal potential of plants. Gains in SR lag behind expected climate warming (Menéndez *et al.* 2006), and a combination with dispersal models would be useful to reduce this uncertainty (Thuiller *et al.* 2008). Given the uncertainties in bioclimatic modelling linked to biases in data sampling, modelling technique, spatial autocorrelation, biotic interaction or species evolution (Heikkinen *et al.* 2006), the findings of range change can serve only to assist, not to determine nature conservation policy (Dormann 2007). The nonlinear response patterns obtained with the current study support the goal for a 2°C temperature stabilization target, also to limit potential threats to biodiversity.

We acknowledge the support of the projects 'Flora & Climate' (FKZ 80581001) (S.P. and I.K.) funded by the German Federal Agency for Nature Conservation and Assessing Large scale environmental Risks for biodiversity with tested Methods (ALARM, GOCE-CT-2003-506675; Settele *et al.* 2005; I.K., F.B. and S.K.), Minimisation of and Adaptation to Climate change Impacts on biodiversity, No. 044399 (MACIS; I.K. and W.T.) and Challenges in assessing and forecasting biodiversity and ecosystem changes in Europe, No 066866 GOCE (ECOCHANGE; W.T.) funded by the European Commission's FP6. For their valuable comments and supplying material, we particularly thank Jessica Bergmann, Gudrun Carl, Eva Küster, Wolfgang Cramer, Stefan Fronzek, Thomas Hickler, Ralf Ohlemüller and Oliver Schweiger.

- Dormann, C. F. 2007 Promising the future? Global change projections of species distributions. *Basic Appl. Ecol.* **8**, 387–397. (doi:10.1016/j.baae.2006.11.001)
- European Soil Database (v. 2.0) 2004 European Soil Bureau Network and the European Commission, EUR 19945 EN. See <http://eusoils.jrc.it>.
- Heikkinen, R. K., Luoto, M., Araújo, M. B., Virkkala, R., Thuiller, W. & Sykes, M. T. 2006 Methods and uncertainties in bioclimatic envelope modelling under climate change. *Prog. Phys. Geogr.* **30**, 751–777. (doi:10.1177/0309133306071957)
- Jalas, J. & Suominen, J. 1972–2004 *Atlas Florae Europaeae*. Helsinki, Finland: The Committee for Mapping the Flora of Europe and Societas Biologica Fennica Vanamo.
- Jetz, W., Wilcove, D. S. & Dobson, A. P. 2007 Projected impacts of climate and land-use change on the global diversity of birds. *PLoS Biol.* **5**, 1211–1219. (doi:10.1371/journal.pbio.0050157)
- Kier, G. & Barthlott, W. 2001 Measuring and mapping endemism and species richness: a new methodological approach and its application on the flora of Africa. *Biodiv. Conserv.* **10**, 1513–1529. (doi:10.1023/A:1011812528849)
- Luoto, M., Virkkala, R. & Heikkinen, R. K. 2007 The role of land cover in bioclimatic models depends on spatial resolution. *Global Ecol. Biogeogr.* **16**, 34–42. (doi:10.1111/j.1466-8238.2006.00262.x)
- Mac Nally, R. 1996 Hierarchical partitioning as an interpretative tool in multivariate inference. *Aust. J. Ecol.* **21**, 224–228. (doi:10.1111/j.1442-9993.1996.tb00602.x)
- Menéndez, R., González Megías, A., Hill, J. K., Braschler, B., Willis, S. G., Collingham, Y., Fox, R., Roy, D. B. & Thomas, C. D. 2006 Species richness changes lag behind climate change. *Proc. R. Soc. B* **273**, 1465–1470. (doi:10.1098/rspb.2006.3484)
- Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M. & New, M. 2004 *A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100)*. Working paper 55. Norwich, UK: Tyne Centre for Climate Change Research, University of East Anglia.
- Mucher, C. A., Steinnocher, K. T., Kressler, F. P. & Heunks, C. 2000 Land cover characterization and change detection for environmental monitoring of pan-Europe. *Int. J. Remote Sens.* **21**, 1159–1181. (doi:10.1080/014311600210128)
- Parmesan, C. 2006 Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.* **37**, 637–669. (doi:10.1146/annurev.ecolsys.37.091305.110100)

- Pearson, R. G. & Dawson, T. P. 2003 Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecol. Biogeogr.* **12**, 361–371. (doi:10.1046/j.1466-822X.2003.00042.x)
- Pearson, R. G., Dawson, T. P. & Liu, C. 2004 Modelling species distributions in Britain: a hierarchical integration of climate and land-cover data. *Ecography* **27**, 285–298. (doi:10.1111/j.0906-7590.2004.03740.x)
- Rounsevell, M. *et al.* 2006 A coherent set of future land use change scenarios for Europe. *Agric. Ecosyst. Environ.* **114**, 57–68. (doi:10.1016/j.agee.2005.11.027)
- Settele, J. *et al.* 2005 ALARM: Assessing LArge scale environmental Risks for biodiversity with tested Methods. *GALA* **14**, 69–72.
- Spangenberg, J. H. 2007 Integrated scenarios for assessing biodiversity risks. *Sustain. Dev.* **15**, 343–356. (doi:10.1002/sd.320)
- Thuiller, W. 2003 BIOMOD—optimizing predictions of species distributions and projecting potential future shifts under global change. *Global Change Biol.* **9**, 1353–1362. (doi:10.1046/j.1365-2486.2003.00666.x)
- Thuiller, W., Lavorel, S., Araújo, M. B., Sykes, M. T. & Prentice, C. 2005 Climate change threats to plant diversity in Europe. *Proc. Natl Acad. Sci. USA* **102**, 8245–8250. (doi:10.1073/pnas.0409902102)
- Thuiller, W. *et al.* 2008 Predicting global change impacts on plant species' distributions: future challenges. *Perspect. Plant Ecol. Evol. Syst.* **9**, 137–152. (doi:10.1016/j.ppees.2007.09.004)